INVESTIGATION OF EFFECT OF THROTTLING AIR INTAKE UPON CERTAIN OPERATING CHARACTERISTICS OF A PRE-COMBUSTION CHAMBER DIESEL ENGINE.

By

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Investigation of Effect of Throttling Air Intake Upon Certain Operating Characteristics of a Pre-Combustion Chamber Diesel Engine

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Grad. (United States Naval Academy) 1930

THESIS

Submitted in partial satisfaction of the requirements for the degree of

MASTER OF SCIENCE

in

Mechanical Engineering

in the

GRADUATE DIVISION

of the

UNIVERSITY OF CALIFORNIA

Approved:

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Committee in Charge

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## ACKNOWLEDGMENT

The writer wishes to express his sincere appreciation to Professors C.J. Vogt and E.J. Howe for their advice, suggestions and guidance throughout the course of this investigation.

Acknowledgment is also made to the Caterpillar Tractor Company for their courtesy in providing the engine used.

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## INTRODUCTION

While the normal operating condition of a carburetor engine is with throttled intake (except for maximum power), the air intake of a compression-ignition engine is not throttled under ordinary conditions since the control of power is accomplished by varying the volume of the fuel charge. However, certain types of installations impose restrictions in the intake system which produce a considerable throttling effect. Common examples of this effect are found in the use of air cleaners, the long and restricted induction systems of submarines or in the operation of Diesel engines at high altitudes. It was to determine the effect of these conditions upon the operation of the engine that the subject investigation was undertaken.

## THE EXPERIMENTAL SETUP

A four-cylinder, four-cycle Caterpillar D-4400 Diesel engine, having a 4-1/4-in. bore, 5-1/2-in. stroke, 312-cu in. piston displacement, a 16:1 compression ratio, was direct-connected to a 50-hp electric cradle dynamometer. The air induction system consisted of a 1-1/2-in. diameter bell-mouthed orifice inserted in one end of a 30-gal steel drum used as a surge tank. Connecting the surge tank to the air cleaner installed at the engine intake manifold was an 8-ft section of 2-1/2-in. inside diameter pipe together with a short section of rubber hose. A gate valve was inserted in this line near the exit from the surge tank to act as the intake air throttling valve. An inclined manometer (Ellison draft gauge) was used to measure the pressure drop across the orifice and thereby measure the rate of airflow through the orifice. A 195.5 ml burrette was installed for measuring fuel consumption. A three-way

valve in the fuel supply line to the fuel injection pumps transferred the fuel supply from the regular engine fuel system to the burette during fuel consumption runs. A synchronized revolution counter and electric timer served to count the number of revolutions made and the elapsed time of each run. The jacket-cooling system was not changed and water temperature was controlled by the regular radiator and fan. A chromel-alumel thermocouple in a quartz radiation shield was installed in the exhaust pipe between the exhaust manifold and the muffler. The 6-in. long, 1/4-in. inside diameter quartz tube open at both ends projected into the center of the exhaust pipe. The thermocouple junction was located 1/4 of an inch inside the inner end of the quartz tube. The difference in pressure between the exhaust gases and the atmosphere caused the hot gases to sweep through the tube and by the thermocouple with a moderate velocity. The exhaust gas sampling connection was made at the junction of the exhaust manifold and the exhaust pipe. Views of the experimental setup are shown in Figs. 1, 2 and 3 which follow this section.

A high-grade Diesel fuel was used for all runs. This fuel had a viscosity at 100° F. of 40 seconds Saybolt Universal; its specific gravity at 60° F. was 33.2° A.P.I.; and its cetane number was greater than 45.

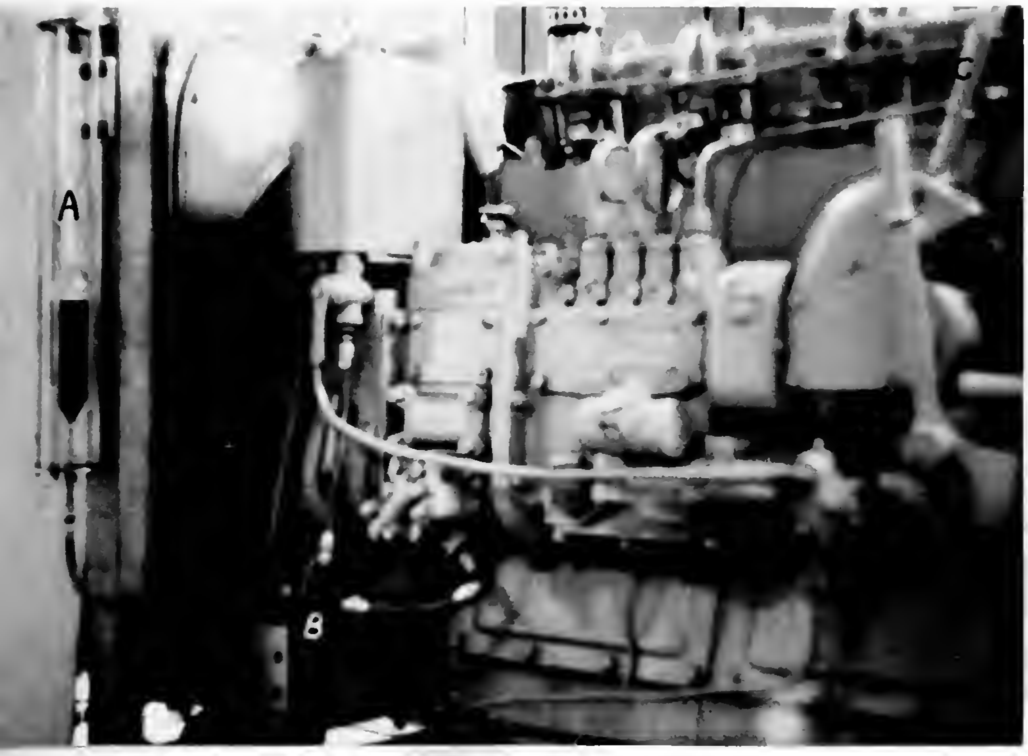


FIG. 1. A VIEW OF THE LEFT SIDE OF THE ENGINE.

A. Fuel measuring burrette.

B. Three-way cock.

C. Fuel throttle or governor control lever.

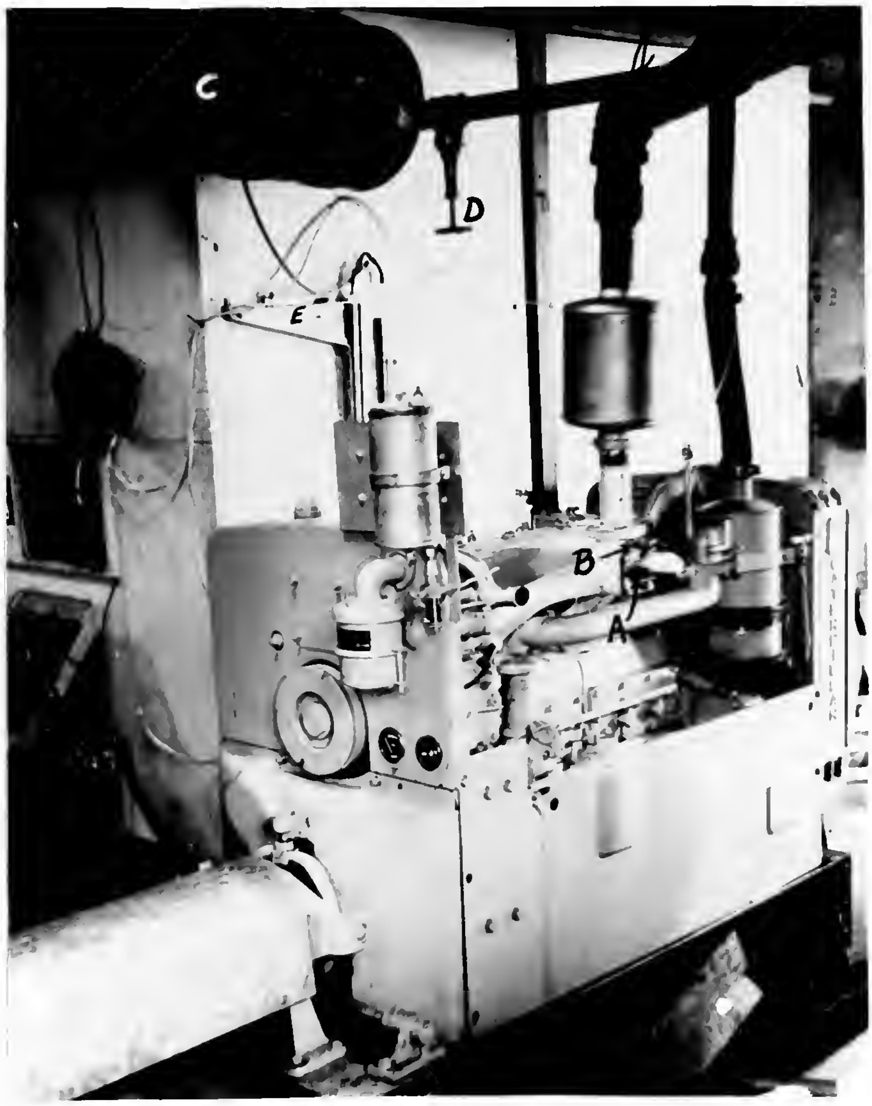


FIG. 2. A VIEW OF THE SETUP FROM THE RIGHT SIDE OF ENGINE.

A. Exhaust gas sample connection.

B. Exhaust temperature thermocouple position.

C. Air-metering orifice.

D. Intake air throttling valve.

E. Draft gauge measuring pressure drop across orifice.

FIG. 3. A VIEW OF THE EXHAUST GAS COLLECTING AND ANALYZING APPARATUS.

A. Orsat apparatus taking a 100 ml sample.

B. Collecting and mixing tank.

C. Connection from exhaust manifold of engine.

D. Vent.

E. Water supply.

F. Water drain.

G. Connection to Orsat apparatus.

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## TEST PROCEDURE

The primary purpose of this investigation was to determine the variation in fuel consumption for a constant load and speed when the charge efficiency was varied by throttling the air intake. Of secondary importance was the effect of reduction in charge efficiency upon the exhaust temperatures, jacket-cooling water temperatures, detonation and soot formation.

Runs were made at 900 rpm and 1300 rpm, brake mean effective pressures of 60, 45, 30 and 15 lb/sq in., and charge efficiencies, referred to dry air at 68° F. and 14.7 lb/sq in., of from .60 to approximately .90.

Before starting runs the engine was brought up to operating temperatures. The governor was set to give the desired speed; the field and armature rheostats were adjusted to give the desired load; and the air intake throttle was adjusted to allow the induction of the desired amount of air. When the engine had settled down

to steady operating temperatures the valve in the fuel line was shifted so that the engine was taking fuel from the burette. When the fuel level in the burette passed the upper mark a switch was closed which started the electric timer and inserted the revolution counter. When the lower mark was passed the switch was opened, stopping the timer and the revolution counter. The air temperature at the orifice, jacket-cooling water temperature, fuel temperature, exhaust gas temperature and reading of the pressure drop across the air-metering orifice were recorded during the run. The exhaust gas sample was also collected during the run and analyzed immediately using the standard Orsat apparatus. After a run was completed the fuel supply to the engine was shifted back to normal and the burette refilled.

The quantity of air supplied was computed from the barometric pressure, air temperature and pressure drop across the orifice. This figure was converted to charge efficiency referred to standard conditions (dry air at 68° F. and 14.7 lb/sq in.) and is recorded as such. The effect of atmospheric humidity was found to be negligible. The capacity of the fuel burette was converted to pounds, using the fuel temperature to obtain the correct fuel density; and the fuel consumption was recorded as pounds of fuel per revolution.

Soot formation was measured by using the Ackermann Combustion Triangle [1]. The diagram is entered with per cent carbon dioxide and per cent oxygen in dry exhaust gas as arguments. Soot is recorded as that fraction of the carbon in the fuel which is not burned.

The air temperature at the air-metering orifice was measured with a mercury thermometer. The fuel temperature was obtained by means of a copper-constantin thermocouple. Jacket-cooling water temperature was given by the regularly installed thermometer.

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[1] G. Ackermann, Dr. Ing, Combustion Triangle at Soot Formation - Das Verbrennungsdreieck bei Russbildung, Forshungsheft 366 - May June, 1934.

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## EXPLANATION OF TEST CURVES

The results of this investigation are shown in Figs. 4 to 7 inclusive. Fig. 4 shows the relation between fuel consumption and charge efficiency for different brake mean effective pressures and constant speeds of 900 and 1300 rpm. Fig. 5 shows the relation between fuel economy and charge efficiency for different brake mean effective pressures and constant speeds of 900 and 1300 rpm. Fig. 6 and Fig. 7 show, respectively, the relation between exhaust temperatures and charge efficiency and between unburned carbon in exhaust and charge efficiency for different brake mean effective pressures at 900 rpm.

Fig. 4: - These curves present in graphical form the major portion of the investigation. In addition to showing the relation between fuel consumption and charge efficiency it shows the relation between each of the foregoing and air to fuel ratio (per cent theoretical air).

The dashed and full lines show the variation in fuel consumption with change in speed. The increments of brake mean effective pressure chosen represent full load, three-quarter load, half load and one-quarter load conditions.

Fig. 5: - Fig. 5 presents the same data as Fig. 4 in more conventional units and in a slightly different form. However, it was not possible to present in this figure the lines of constant per cent theoretical air.

Fig. 6: - The actual values of exhaust temperature presented in these curves are not particularly significant because the design of the thermocouple was not intended to produce extremely accurate results. However, the manner in which the temperature varied with charge efficiency for the different brake mean effective pressures is considered both interesting and significant.

Fig. 7: - These curves are interesting in that they show the effect of charge efficiency and load upon the completeness of combustion of the fuel.

The extent of the curves in all the figures from 4 to 7 was limited by the following conditions: The charge efficiency could not be materially reduced below a value of .60 because of the severe detonation which resulted. The upper limits of charge efficiency represent unthrottled conditions. The 60 lb/sq in. brake mean effective pressure curves were terminated when the fuel pump reached

the limit of its rack setting and was injecting the maximum quantity of fuel.

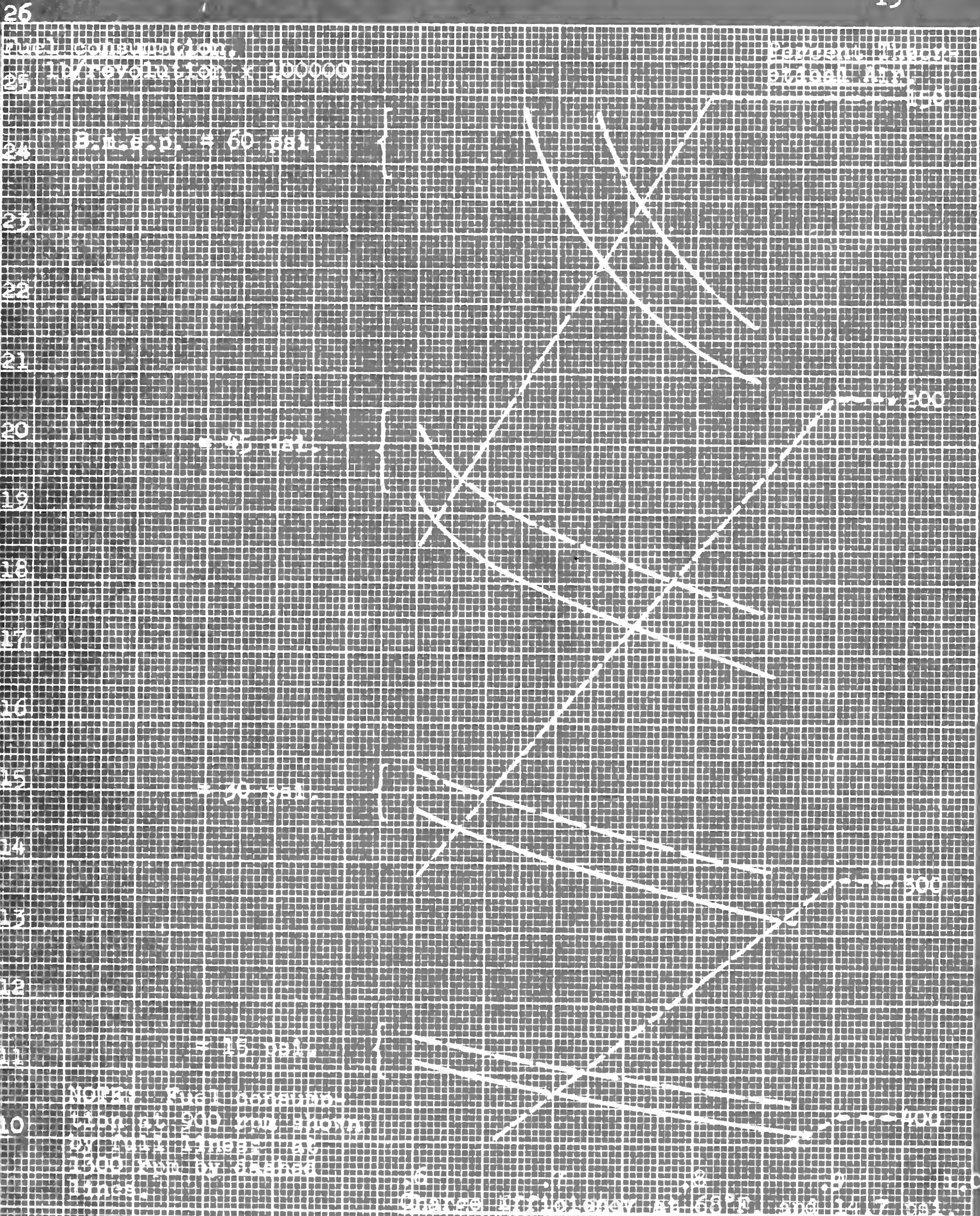


Fig. [illegible]. Relation Between Fuel Consumption and Charge Efficiency for Different Brake Mean Effective Pressures and Constant Speeds of 900 and 1300 R.P.M.

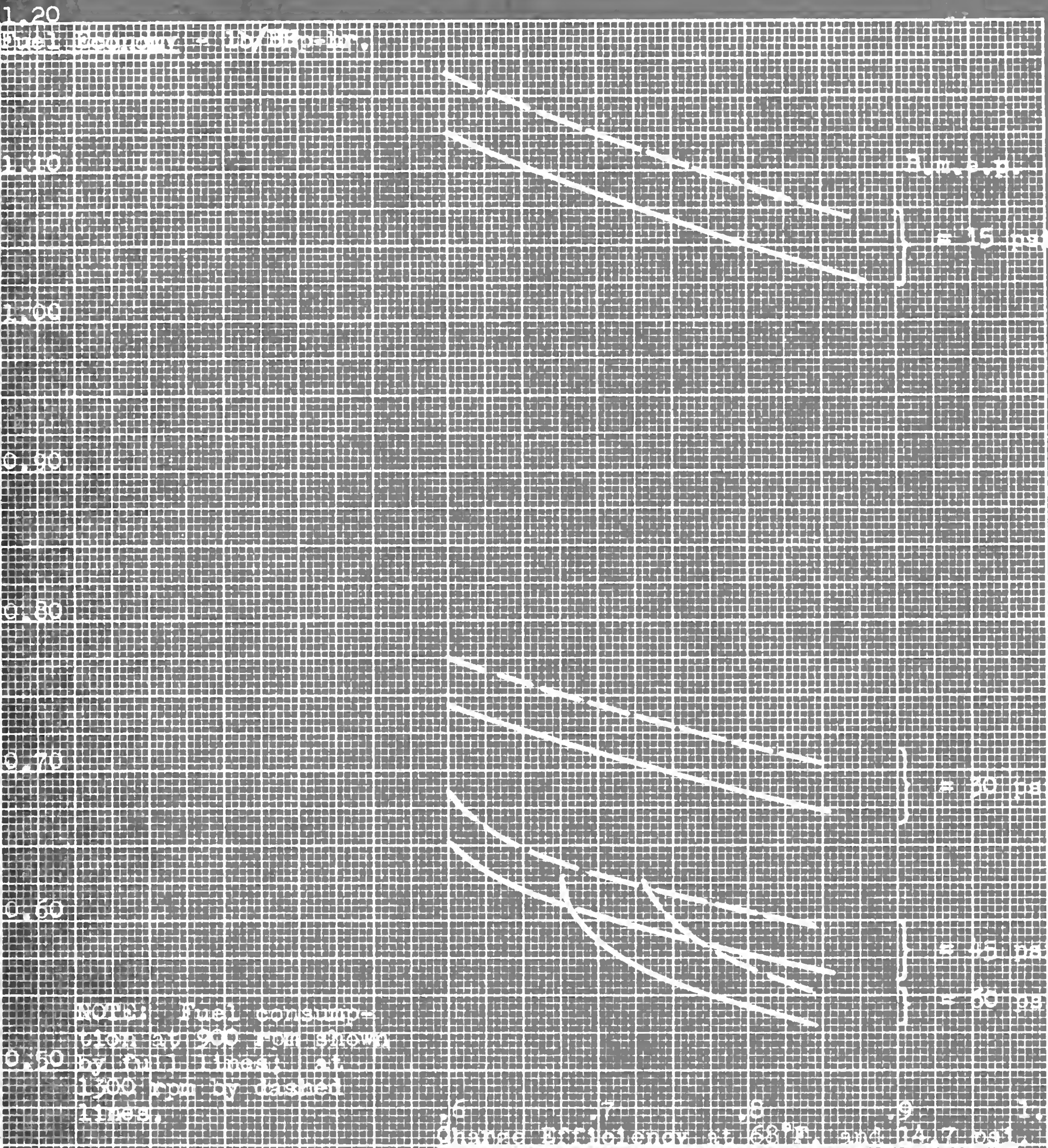


Fig. 5 Relation Between Fuel Economy and Charge Efficiency for Different Brake Mean Effective Pressures and Constant Speeds of 900 and 1300 R.P.M.

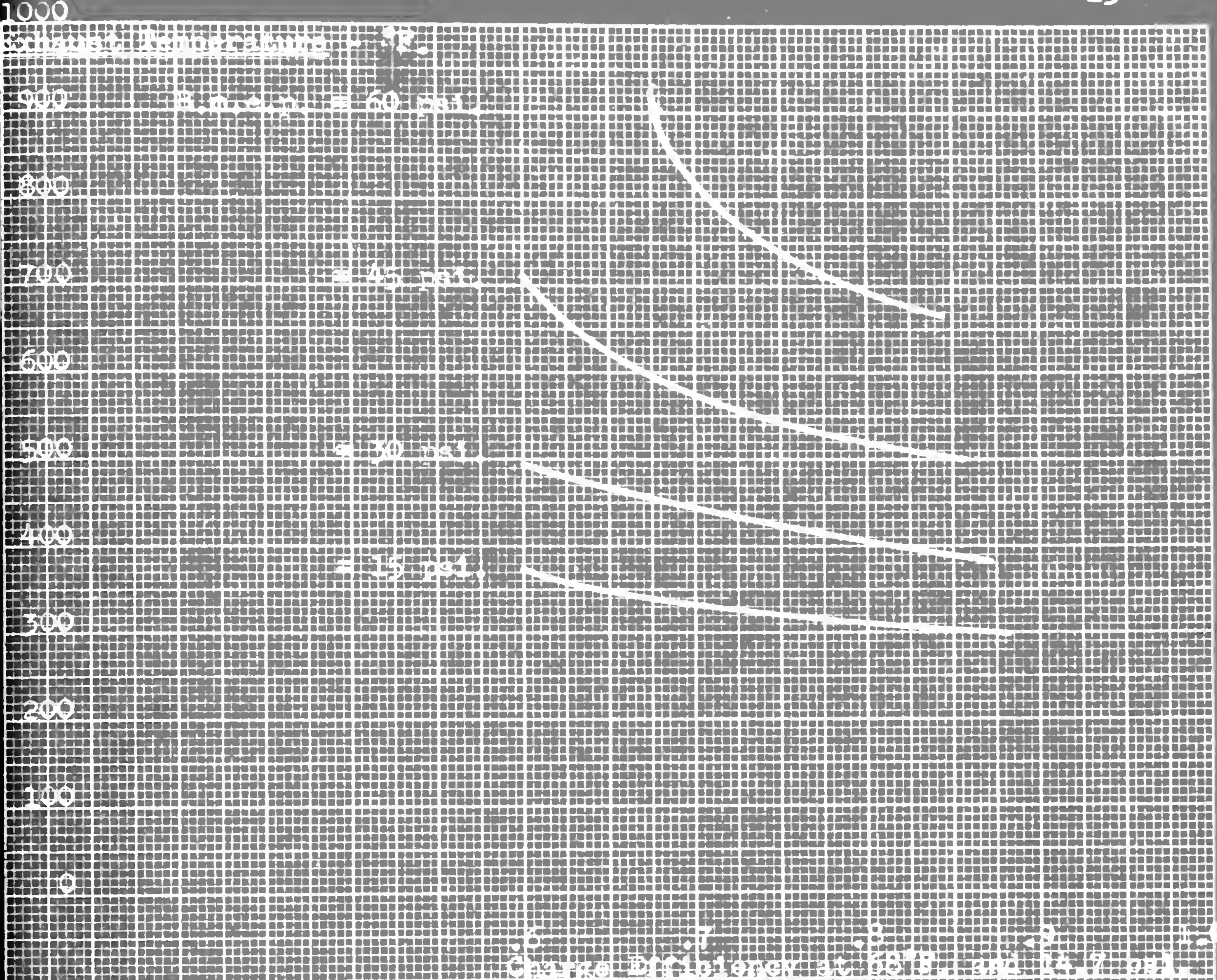


Fig. 6 Relation Between Exhaust Temperatures and Charge Efficiency for Different Brake Mean Effective Pressures at 900 R.P.M.

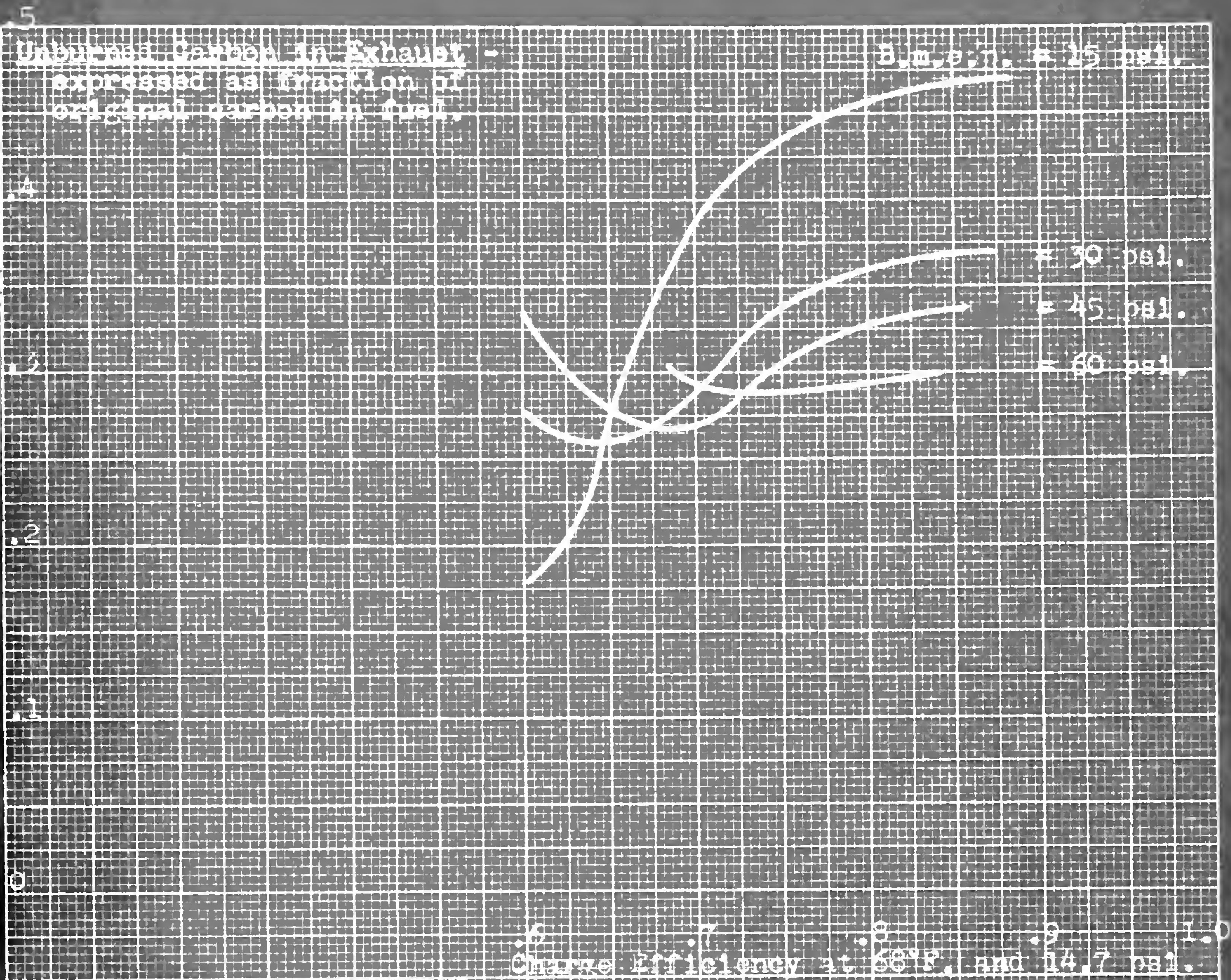


Fig. 7 Relation Between Unburned Carbon in Exhaust and Charge Efficiency for Different Brake Mean Effective Pressures at 900 R.P.M.

## DISCUSSION

The fuel consumption of an internal combustion engine is affected by the load, speed, charge dilution, friction losses, losses to jacket-cooling water, losses to exhaust gases, pumping losses, air to fuel ratio, atmospheric temperature, pressure and humidity, the ignition and combustion of the fuel. Since this investigation was conducted in such a way that the speed and load was maintained constant for any single run and since the atmospheric temperature, pressure and humidity remained substantially constant for all runs these factors can be subtracted from the list of variables.

Charge dilution. Charge dilution is caused by the residual exhaust gases which remain in the clearance space at the end of the exhaust stroke. The volume of these gases is constant but their weight is dependent upon the exhaust pressure and temperature. As the load is increased the

exhaust pressure rises tending to increase the weight of the residual gases. At the same time the temperature rises tending to decrease the weight. The exhaust gases as they mix with the incoming charge increase its temperature, thereby decreasing the charge efficiency for a given suction pressure. The adverse effect of charge dilution upon the thermodynamics of the cycle is to inhibit combustion by decreasing the ratio of oxygen in the charge to the nitrogen and carbon dioxide present. This adverse effect increases with decrease in charge efficiency and also with decrease in air to fuel ratio. In the first case the amount of oxygen brought in by the fresh charge is reduced; and in the second, there is less oxygen and more carbon dioxide remaining in the residual gases. Because compression-ignition engines have relatively small clearance volumes and operate with considerable excess air charge, dilution is much less important than in carburetor engines.

Friction losses. Friction losses are functions of engine speed and piston pressures and increase with an increase in either of the two. Since the influence of other factors is likely to be small and since the brake mean effective pressure and speeds were maintained constant for each run it is believed that the friction losses for each run remained substantially constant.

Losses to cooling water. If the heat release within the cylinder is kept constant (viz. constant fuel charge), and, by throttling, the air charge is decreased, the result will be an increase in the temperature of the combustion gases during the power and exhaust strokes. This is due to the fact that there is a lesser weight of combustion products to absorb the given amount of heat. The effect of increased specific heats and dissociation at high temperatures work in the direction of decreasing the temperature but are overshadowed by the mass effect. Since the temperature during the intake stroke will be relatively unaffected, the net result is to increase the average temperature during the cycle with increased throttling of air. The average pressure during the cycle, for a given brake mean effective pressure will remain substantially constant regardless of throttling. Then, since the loss of heat from the gases to the cylinder walls are proportional to $(P^2T)^{1/3}$ [1], the losses to the cooling water will be increased with increased throttling of air.

Losses to exhaust gases. Since, as was shown above,

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[1] Nusselt, Wilhelm, Der Wärmeübergang in der Verbrennugskraftmaschine, Forschungsarbeiten, Heft 300.

the gases of combustion are hotter for increased air throttling, it follows that the loss to the exhaust gases will be greater.

Pumping losses. One effect of a throttle intake on the indicator card of an engine is to lower the suction line. Since the exhaust line will be affected very little, the resulting negative loop formed by the exhaust and intake strokes will become larger. This area represents the pumping losses, and with increased throttling may become fairly large.

Air to fuel ratio. For a given fuel input, reducing the air charge results in a decrease in the air to fuel ratio, which in turn will reduce the cycle efficiency [1]. The effect is much more pronounced at lower values of air to fuel ratio, the efficiency curve flattening out considerably at about 300 per cent theoretical air.

Ignition and combustion. The reduction in the pressure at the beginning of the compression stroke will cause a reduction in the compression pressure and temperature, which will affect the ignition and combustion of the fuel.

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[1] G.A. Goodenough and J.B. Baker, "A Thermodynamic Analysis of Internal Combustion Engine Cycles"; Bull. 160 of the Eng. Exp. Sta. of the Univ. of Ill.

This, in turn, will affect the shape of the indicator diagram and the thermodynamics of the working process.

It was not found practicable to fit engine indicators on the engine used in the investigation; and without indicator diagrams to give some idea of the way in which combustion takes place, it is almost impossible to discuss the effect of throttling air intake upon the thermodynamic cycle. It would be inadvisable to apply conclusions concerning ignition delay and rate of pressure rise drawn from any one engine to another engine in which the process of injection and distribution of the fuel is not exactly similar. Judge [1] lists the factors which will decrease the ignition delay and increase the speed of combustion as:

(1) increase in turbulence;

(2) increase in compression pressure;

(3) supercharging;

(4) doped fuels.

Since throttling the air intake reduces the compression pressure and is the inverse of supercharging it may be assumed that it will increase the ignition delay and af-

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[1] A.D. Judge, "High-Speed Diesel Engines". Chapter on combustion.

fect the combustion process adversely.

Confirming this assumption, P.H. Schweitzer's work [1] on Diesel knock, in which the air intake of a compression-ignition engine was throttled, revealed that under throttled conditions the peak pressures were decreased although the rate of pressure rise (the governing factor in detonation) increased. The ignition delay was also increased. The result of this reduction in peak pressures and increase in ignition delay would be a decrease in the average expansion ratio of the engine, thereby decreasing the efficiency of the cycle.

<u>Summary</u>. On the basis of theoretical considerations and the results of previous investigations it has been shown in the foregoing discussion that a decrease in charge efficiency increases losses to cooling water, losses to exhaust gases and pumping losses. It also increases charge dilution, air to fuel ratio, ignition delay and speed of combustion, and thereby decreases the cycle efficiency. The drop in cycle efficiency due to these effects is more rapid under full load than under light load conditions.

<u>Agreement with experimental results</u>. The experimental results shown in the curves of Figs. 4 and 5 are in gen-

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[1] P.H. Schweitzer, "Diesel Knock"; <u>Proc. Amer. Soc. Mech. Engrs</u>. Nov. 1933.

eral agreement with the above theory and previous investigations. The slope of the curves for low brake mean effective pressures is relatively flat but shows a definite increase in fuel consumption with decrease in charge efficiency. While for high brake mean effective pressures the slope increases rapidly with decrease in charge efficiency.

The increase in temperature of the exhaust gases shown in Fig. 6 substantiate the statement that losses to exhaust gases increase with decrease in charge efficiency.

There was noted, but not recorded elsewhere in this report, a definite increase in jacket-cooling water temperature with decrease in charge efficiency. The rises in temperature during the 900 rpm runs from the unthrottled to the limit of the throttled air intake conditions were as follows:

(1) for a bmep of 15 lb/sq in. 4° F.;

(2) for a bmep of 30 lb/sq in. 5° F.;

(3) for a bmep of 45 lb/sq in. 7° F.;

(4) for a bmep of 60 lb/sq in. 9°F.

These results agree with the statement that there would be greater losses to the jacket-cooling water with decrease in charge efficiency.

It will be noted in Fig. 7 that as the charge efficiency decreased there was an increase in the completeness of combustion of fuel, which was greater under light load

conditions than under fullload conditions. This would counteract to some extent the adverse effects upon cycle efficiency of decrease in charge efficiency; and may explain the flatness at low loads of the fuel consumption curves in Figs. 4 and 5.

## CONCLUSIONS

The throttling of the air intake of a pre-combustion chamber Diesel engine delivering a constant horsepower output at constant speed creates the following effects:

(1) Decreases the overall efficiency and fuel economy of the engine.

(2) Increases the heat losses to the exhaust gases and to the cooling water.

(3) Increases the pumping losses.

(4) Detracts from the smoothness of running of the engine and when the charge efficiency is sufficiently reduced causes severe detonation.

(5) Increases ignition delay.

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Thesis 6321
T8 Trippensee

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